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Water loss from various cropped surfaces.

by

N. E. Rider.

(Meteorological Office)

METEOROLOGICAL OFFICE
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Summary

An account is given of some observations designed to evaluate the daily water losses from surfaces carrying crops of different size and shape which were transpiring at their potential rates. The familiar aerodynamic method is used and it is shown that considerable differences in water loss occur between fallow land, pasture, peas, and brussels sprouts, the differences being too large to be accounted for by possible errors in the observations or method employed.

Introduction

Penman's (1948) method for the calculation of evaporation from land surfaces has led to the adoption of a scheme for the computation of irrigation need which is gradually finding application in day to day farming practice (Pearl and others, 1954). In the present paper it is not proposed to discuss the basis of Penman's method for the calculation of the transpiration from a turf surface when the water supply is in no way limiting, that is the potential transpiration, by the substitution of readily available meteorological data in semi-empirical and empirical equations. This has already been done at some length by Pasquill (1950). Here we shall give the results of an experimental study of the variation in the rate of water loss from more or less adjacent areas carrying different crops. The investigation was undertaken in an attempt to test the adequacy of the assumption made in the general application of Penman's work that the potential transpiration from any normal cropped surface is the same as that from grass provided that the crop has the same colour as grass and completely covers the ground. The aim of irrigation is to add just sufficient water to the crop to maintain the actual transpiration rate at its potential value, which is controlled by the weather alone, since there is evidence that maximum growth takes place when this condition is satisfied. At present it is the practice to irrigate crops of very different size and character equally and this is a direct consequence of the assumption of equal potential transpiration. It is assumed in the last statement that the 'root constant' is identical for the crops under consideration. The root constant is the maximum soil moisture deficit (usually expressed in in. or cm.) that can be built up before the transpiration rate is checked. Irrigation is started when this deficit is reached.

In the work to be described the aerodynamic method is used to evaluate the daily water losses. This method has been under investigation at Cambridge for a number of years and the physics underlying it, together with the limitations and precautions that must be observed in its use, are now fairly well understood. It will be recalled that the validity of the Thornthwaite and Holzman (1939) equation, as modified by Pasquill (1949a),

/E =

$$E = \frac{\rho k^2 (u_2 - u_1)(q_1 - q_2)}{\left[\ln \frac{z_2 - d}{z_1 - d}\right]^2} \qquad \ldots\ldots 1$$

in which E is the rate of evaporation, k is von Karman's constant, ρ the air density, d the zero plane displacement and u_1, u_2, q_1 and q_2 are the wind speeds and specific humidities at the heights z_1 and z_2, has been demonstrated (Pasquill 1949a, 1950b, Rider 1954a) and that a summary of these investigations together with some discussion on the difficulties and accuracy to be expected in its application has been given by Rider (1954b).

Observational aspects

A site about 6 miles NW. of Cambridge was used. It was in level open country and throughout the period covered by the observations a pasture and a fallow field were generally available. At various times it was possible to expose apparatus in a pea field and in a field of fully grown brussels sprouts which were being allowed to run to seed. All these sites were within a circular area of some 500 m. diameter and therefore exposed to the same weather. The soil type of each was the same. The initial plan for the observations which had to be modified from day to day to meet ruling conditions was to undertake a series of six day runs, the first two and last two days of each series being occupied with control observations. It was hoped to get a number of such observations at intervals of about four weeks throughout the growing season but it proved impossible to maintain a strict schedule as this work had to be done in fine weather as well as give way to farming requirements. In the event three periods were covered. The first extended from 19 May to 7 June, the second from 16 to 24 June and the third from 7 to 14 July, 1955. There was also an initial day's observation on 9 to 10 May to test the apparatus, three sets of which were built for the investigation. The sites on which the apparatus was exposed during these periods can be seen by referring to Table I. Initially on 9 May the pasture had a grass length of about 15 cm. The grass grew steadily throughout the first period of observation until on 7 June it had reached a height of about 30 cm. Cattle were then sent into the field and when work recommenced on 18 June the grass had been reduced to a fairly uniform height of about 10 cm., after which it again grew steadily until the measurements finished. These changes in the length of the grass are reflected in the values of d given in Table I. The bare soil was harrowed before measurements started and occasionally during the observational period it was 'cultivated' to keep weeds down. The surface consisted of parallel ridges and troughs having an amplitude of about 20 cm. The brussels sprouts were fully grown plants about 1 m. high and when apparatus was placed over them they were on the point of flowering. Although the stems of these plants were fairly widely spaced the tops were bushy and formed a complete cover over the ground. The peas were just coming into flower on 18 June and had a height of about 60 cm. They covered the ground with a dense mat of green vegetation and when in pod in July this cover was even denser although there was no apparent increase in crop height.

The minimum requirements for the calculation of the rate of evaporation from Eq.1 are the measurement of humidity at two heights and the measurement of wind speed at three heights, the wind speed at the third height being required for the determination of d, since the latter can theoretically be obtained by the use of the equation

$$\frac{u_3 - u_2}{u_2 - u_1} = \frac{\ln(z_3 - d) - \ln(z_2 - d)}{\ln(z_2 - d) - \ln(z_1 - d)} \qquad \ldots\ldots 2$$

when neutral conditions of stability hold in the layer of air concerned. However, previous experience when working over an oat field (Rider, 1954c) has led to the conclusion that it is essential to have measurements of wind speed at more than three heights in order to arrive at reliable values of d as it is not possible to measure the wind speeds with sufficient precision for use in Eq.2, and a graphical method in which smoothing is possible has to be used. For this wind speeds at five or more heights are desirable, and in the majority of the observations this number of anemometers was exposed with each set of apparatus at heights up to 2.5 m. Fig.1 shows three sets of apparatus standing on the pasture on 10 May when only three anemometers per set were available. The anemometers were the sensitive cup type arranged to operate electromagnetic counters at some distance from the position of exposure. These counters were photographed every hour to provide a record of the runs of wind and hence of the mean hourly wind speeds. Each humidity mast carried two psychrometers, the psychrometers having dry and wet bulb thermo-electric thermometers which were aspirated at 3 m./sec. The thermometers were arranged in 'tandem' along the axis of a copper tube with the dry bulb in front of the wet bulb. The arrangement is shown in Fig.2. Outside the inner tube another copper tube was mounted co-axially with the first. In use air passed down the space between the two tubes at the same rate as over the thermometers. All metal surfaces were plated and the thermometers had a lag coefficient of about 75 sec. These housings were designed to overcome some undesirable features found in those used in previous work which were based on Pasquill's (1949b) design. In that design rectangular section tufnol tubes were used and it was found that when solar radiation falls on one side of this housing a difference of temperature of up to 0.5°F. can occur between two dry bulb thermometers mounted in it when the aspiration rate is as high as 3 m./sec. In the present housing the thermometer bulbs are mounted symmetrically with respect to the walls and the much higher conductivity of the copper tends to even up the temperature differences around the housing when sunshine is falling on one side. The one precaution to be taken is that the housing must not be directed at a low sun. No temperature differences have been detected between dry bulbs exposed in this housing in test runs and, further, the absolute temperature errors, although of secondary importance in this application, are considerably less than in the Pasquill type.

The housings are arranged to plug into tufnol collars which are attached to the mast. Each collar is provided with a butterfly valve which could be locked in position after being adjusted to provide the required rate of aspiration, the latter being arranged to be the same at each of the four mounting positions which were 25 cm. apart in height. The two positions not in use at any time were closed by corks, and the overall heights of the masts could be adjusted when necessary by lengthening the supports. The masts themselves were hollow, so providing the link between the aspiration fans and the psychrometers. The thermo-electric thermometers at the greater height were each provided with two thermo-junctions and one dry and one wet junction were used in conjunction with a standard junction kept in melting ice. The other two were connected in series with the corresponding junctions in the lower psychrometer. The details of the wiring and recorders have been given previously (Rider, 1954c, Fig.2). It is sufficient to recall here that two classes of recorder are used. The first is a comparatively insensitive type which is used to provide a record of the dry and wet bulb temperatures at the greater height (t_2 and t'_2), and the second is a sensitive photographic recorder which provides a record of the

/dry

dry and wet bulb temperature differences between the two heights, $(t_1 - t_2)$ and $(t'_1 - t'_2)$. The temperatures are recorded to 0.1°F. and the temperature differences to 0.01°F. These limits of measurement enable the vapour pressure differences $(e_1 - e_2)$ to be obtained to 0.01 mb. The masts and recorders were calibrated as single units in the usual way and on the site the wind and temperature recorders associated with each of the three sets of apparatus were grouped together in a hut placed at one corner of the pasture. 200 m. lengths of cable enabled the apparatus to be moved from site to site as required. The main difficulties experienced in the observational work arose from,

(a) the lack of a mains power supply and the enforced reliance on motor generators and batteries

(b) the absence of a darkroom near the site

(c) the rather small areas of brussels sprouts and peas available for the observations. This made it necessary to site the apparatus near the downwind side of the fields to obtain an ample fetch over a uniform surface and changes in wind direction of more than about 45° made it necessary to abandon the run and resite the apparatus for another attempt, and

(d) the time taken to move the apparatus from site to site with the limited labour available.

Calculation of the water loss and discussion of the results

Eq.1 is strictly only valid in neutral conditions of atmospheric stability, its use in unstable and stable conditions leading to an underestimation and overestimation of the rates of evaporation respectively. However, since the degree of departure from neutral conditions is controlled by the vertical wind shear as well as by the departure from the adiabatic lapse rate it is possible to keep the systematic errors which arise from the neglect of the stability effect to a minimum by siting the psychrometers and anemometers at a low height above the vegetation (Pasquill 1949a, Rider 1954c). It has been estimated that above an oat field and a pasture, provided this precaution is taken, the underestimations in the daily totals of water loss will not exceed 15% and 10% respectively. Moreover in this instance we are endeavouring to compare the differences in water loss between surfaces which are exposed to the same weather and when an underestimate occurs for one site it will occur for another, but since the effective heights of exposure of the apparatus on the sites investigated was not always the same and there were differences in the micrometeorology from site to site the errors were somewhat different in magnitude. Other equations are available for the more precise evaluation of evaporation rate in non-neutral conditions but they contain parameters which are extremely difficult to determine with any confidence for a cropped surface.

From the records hourly mean values of the temperatures, temperature differences and wind speeds were easily obtained, and it only remained to obtain values for d before the rates of evaporation and hence the daily water losses could be calculated from Eq.1 which for practical use is conveniently written as

$$E = \frac{3{\cdot}46 \times 10^{-5}(e_1 - e_2)(u_2 - u_1)}{T\left[\ln \frac{z_2 - d}{z_1 - d}\right]^2}$$

in which e, the vapour pressure, is in mb., u is in cm./sec., z and d are in cm., T is the absolute temperature, and E is in g./cm.^{2}/sec. The method used for the determination of d was to select 'neutral' hours by referring to the records of $(t_1 - t_2)$ and to plot values of u_z against log $(z - d)$ using likely values of d. The best approach to a straight line indicated the required value of d. For this purpose neutral hours were considered to be those for which $(t_1 - t_2)$ did not exceed $\pm 0.05°F.$; the psychrometer heights z_1 and z_2 were always 25 cm. apart. When more than one hour on a particular day gave a different value from another, more weight was given to the hour with the higher wind speeds. When a number of suitable hours occurred a mean wind speed ratio plot was drawn. An example is given in Fig.3, in which the plots for a few single hours and the mean plots are given for the pea and grass surfaces. When working over a tall cereal Rider (1954c) found that the values of d obtained as outlined above showed a variation with wind speed, d increasing with increasing wind speed up to the maximum experienced (about 5 m./sec. at 2 m.). This was considered to be the result of the waving and bending of the crop and it added a complication to the computation of E. In the present observations stiff crops were deliberately chosen in the hope that this feature would not be found. This has proved to be the case, as while there is some variation in d from hour to hour there is no indication of a systematic change with wind speed. One value of d has therefore been used for each day of observation for each surface and these are set out in Table I together with the 24 hour water losses obtained from the computed values of E. In observations 1 to 4, 8, 9, 13, 14 and 19 the three sets of apparatus were exposed over either grass or bare soil and the 24 hour water losses were computed independently from the results provided by each set. It will be seen that these are in reasonable agreement except when the loss is very small. The worst case occurs in observation No. 8 when the gradients of dry and wet bulb temperature were small. The instrumental errors which arise in the main from stray e.m.f. in the thermo-electric circuits tend to produce absolute errors in the vapour pressure differences and hence in the values of E, and when the evaporation is small the relative errors are large. If it had been realised at the start that the evaporation from bare soil would be so small on many occasions compared with that from grass, more effort would have been made to restrict the control observations to the grass surface. Observation No.9 is of interest since although the psychrometers were exposed at different heights for each set, the 24 hour water losses are in reasonable agreement. Some details from one of the control runs are given in Fig.4. In this figure the mean hourly values of the dry and wet bulb temperature differences, $(t_1 - t_2)$ and $(t'_1 - t'_2)$, between the psychrometer heights z_1 and z_2 of 25 and 50 cm., and the values of $(e_{25} - e_{50})$ which were obtained from these differences and the observed values of t'_{50} are shown for observation No. 14. It will be seen that quite small differences in the values of $(t_{25} - t_{50})$ and $(t'_{25} - t'_{50})$ produce appreciable differences in the values of $(e_{25} - e_{50})$ which when multiplied by the wind speed differences etc. produce surprisingly large differences in the hourly values of E. The mean hourly wind speed differences do not themselves vary very much from set to set, nor do the values of t'_{50}. The variations in the dry and wet bulb temperature profiles are probably due in part to genuine point to point differences as well as to deficiencies in the apparatus. The whole range of control observations suggests that, except when the evaporation is small, the three sets give consistent results to within about 20% in the 24 hour water losses.

Turning now to those days on which the three sets of apparatus were exposed over different sites we see that the loss was greater from peas or brussels sprouts than from the pasture in every instance by a factor which varied from day to day and which reached a maximum of about an order of magnitude in observation No.10. Details of this observation have been plotted in Fig.5. A study of this figure shows that the elements follow the usual daily variation but the differences from site to site are considerable. In general the vapour pressure and wind speed gradients are larger over the peas than over the pasture and this, together with the differences in the effective heights of exposure of the anemometers and psychrometers, leads to the much higher values

/of

of E for the peas. An argument sometimes used to support the contention of equal potential transpiration from different surfaces is that the solar and sky energy available to each is the same. A glance at the dry bulb temperatures (t_2) given in Fig.5 shows that over the peas the air was colder than over the grass, and the air over the bare soil was hotter than that over either of the cropped surfaces. This remains true when a correction is applied on the basis of the measured temperature-height profiles to obtain the approximate temperatures at the same effective heights, that is the actual heights measured from the ground minus the appropriate zero plane displacements. It appears that more of the available energy is used in vaporizing water from the peas than from the grass. Similar features can be detected in the results for other days.

It is necessary to produce evidence that the crops were transpiring at their potential rates during the periods covered by these observations. Some support may be had here from calculations based on Penman's method for the computation of accumulated water deficit for a turf covered surface. The accumulated deficit is the excess of potential transpiration over rainfall and these figures for the dates of interest are set out in Table II. According to Pearl and others (1954)

TABLE II

Date 1955	Accumulated deficit (in.)
30/4	1.6
30/5	2.2
15/6	2.5
30/6	3.6
15/7	5.0
30/7	7.5

a deficit of 3 to 5 in. can occur under turf before the actual transpiration falls below its potential rate and for deeper rooted crops the deficit is larger when transpiration is checked. Thus it appears that up to and including observation No.13 on 24/6 we were definitely measuring potential transpiration from the grass surface and may have been doing so throughout the whole series, as the accumulated deficit did not reach 5 in. until after the last day of observation. The peas and brussels sprouts have a root constant which is probably at least equal to that of grass, and they too were probably transpiring at their potential rates. If their root constants are smaller then we must conclude from these results that a rate of transpiration less than the potential rate is greater than the potential rate from turf.

The greatest source of uncertainty in the results given in Table I arises from the lack of a precise knowledge of the values to be given to the zero plane displacements. It is safe to assume that the values used were reliable to the following limits,

grass and bare soil	± 2.5 cm.
peas	± 5 cm.
brussels sprouts	± 10 cm.,

these figures being suggested by the scatter in the individual determinations. Table III shows the changes in the 24 hour water losses which arise from this range of uncertainty in the values to be given to this displacement.

/Table III

TABLE III

Observation No.	Apparatus Set No.	Surface	d cm.	Water loss mm.
5	1	grass	20	2.2 ± 0.3
	2	sprouts	60	3.6 ± 0.9
	3	soil	10	1.2 ± 0.2
10	1	grass	10	0.6 ± 0.1
	2	peas	25	7.4 ± 1.2
	3	soil	10	0.4 ± 0.1
15	1	peas	25	4.4 ± 0.8
	2	soil	10	1.9 ± 0.4
	3	grass	10	2.7 ± 0.6

It is apparent that any likely errors do not affect the general conclusion that must be drawn, namely that the potential transpiration is not the same for all crops which have roughly the same colour and completely cover the ground.

Another and disappointing feature of the results is that there is no steady relationship between the water losses from surface to surface. As far as bare soil is concerned this is easily explained, the rate of loss being controlled by the time that has elapsed since the last fall of rain as well as by the weather. For example during run No.17 there was a heavy thunderstorm from 1700 to 1730 on 11 July and the rate of evaporation on 12 July and 13 July was comparatively high while the soil surface remained wet. By 14 July the surface had dried out and the rate of water loss fell to near its value before the storm. The changes in the ratios of the daily losses of grass to peas or sprouts is not so easily explained. The ratios of the wind speed differences over the 25 cm. height intervals are reasonably constant but the vapour pressure profiles vary in an erratic way from site to site and hour to hour. The changes from lapse to inversion and vice versa in the dry and wet bulb temperature profiles do not occur at the same time over the different sites and it is even possible to have evaporation from one site and condensation on another at the same time. Fig. 5a shows that no inversion occurred over the bare soil during the last hours of 18 June, whereas over the other two surfaces one did occur and was much larger over the grass than over the peas. This type of variation from surface to surface was noted repeatedly and is thought to be a reflection of the role that soil heat plays in the control of microclimate. During the preceding daylight hours the soil temperatures under the bare surface reached much higher values than under the cropped surfaces and a relatively large reservoir of heat was available for liberation at night. This was released sufficiently quickly and proved large enough to offset the inversion which would have otherwise been present.

Conclusion

This report has been written to suggest that the concept of equal potential transpiration irrespective of crop size and character be approached with the utmost caution. It is readily admitted that the values of water loss given in Table I are liable to be in error but in the opinion of the writer no criticism whether from the standpoint of the validity of the aerodynamic formula, of the computations of the zero plane displacements, of the apparatus or method of observation can invalidate the conclusion that real differences exist from surface to surface. The work involved in collecting the observations and in computing the water losses is heavy and similar measurements are not likely to accumulate very quickly in the future. If it is thought worth while to continue this work in the hope that some relationship will be found between the losses from different surfaces in terms of some measurable characteristic of the surfaces then consideration must be given to the provision of power supplies on the site and to the design of an automatic temperature difference integrator.

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Table I

Surfaces and periods of exposure, psychrometric heights, values of zero plane displacement and 24 hour water losses

Observation No.	Period 1955 24 hours commencing G.M.T.	Apparatus Set 1				Apparatus Set 2				Apparatus Set 3			
		Surface	Psychrometer heights (cm.)	d (cm.)	Water loss (mm.)	Surface	Psychrometer heights (cm.)	d (cm.)	Water loss (mm.)	Surface	Psychrometer heights (cm.)	d (cm.)	Water loss (mm.)
1	1400 9/5	Grass	25,50	10	2.0	Grass	25,50	10	2.3	Grass	25,50	10	2.2
2	1200 19/5	Grass	25,50	12	1.7	Grass	25,50	12	1.9	Grass	25,50	12	1.6
3	1700 20/5	Grass	25,50	-	-	Grass	25,50	12	1.9	Grass	25,50	12	2.1
4	1600 25/5	Grass	50,75	15	1.7	Grass	50,75	15	2.5	Grass	50,75	15	2.1
5	2000 26/5	Grass	50,75	20	2.2	Sprouts	125,150	60	3.6	Bare Soil	25,50	10	1.2
6	2300 27/5	Grass	50,75	20	0.7	Sprouts	125,150	60	1.2	Bare Soil	25,50	10	0.5
7	0900 6/6	Grass	50,75	20	2.3	Sprouts	125,150	60	4.3	Bare Soil	25,50	10	0.3
8	1200 16/6	Bare Soil	25,50	10	0.2	Bare Soil	25,50	10	0.3	Bare Soil	25,50	10	0.4
9	1400 17/6	Bare Soil	25,50	10	0.4	Bare Soil	75,100	10	0.5	Bare Soil	50,75	10	0.5
10	1600 18/6	Grass	25,50	5	0.6	Peas	75,100	25	7.4	Bare Soil	25,50	10	0.4
11	1100 21/6	Grass	25,50	5	1.1	Peas	75,100	25	2.3	Bare Soil	25,50	10	1.4
12	1200 22/6	Grass	25,50	10	1.2	Peas	75,100	25	5.0	Bare Soil	25,50	10	
13	1500 23/6	Bare Soil	25,50	10	0.3	Bare Soil	25,50	10	0.4	Bare Soil	25,50	10	0.6
14	1600 7/7	Grass	25,50	10	2.3	Grass	25,50	10	2.9	Grass	25,50	10	2.6
15	0900 9/7	Peas	75,100	25	4.4	Bare Soil	25,50	10	1.9	Grass	25,50	10	2.7
16	1000 10/7	Peas	75,100	25	3.3	Bare Soil	25,50	10	0.4	Grass	25,50	10	2.3
17	1100 11/7	Peas	75,100	25	2.6	Bare Soil	25,50	10	1.1	Grass	25,50	10	2.0
18	1200 12/7	Peas	75,100	25	2.9	Bare Soil	25,50	10	1.7	Grass	25,50	10	1.9
19	1500 13/7	Bare Soil	25,50	10	0.4	Bare Soil	25,50	10	0.6	Bare Soil	25,50	10	0.4

FIG. 1 THREE SETS OF APPARATUS EXPOSED ON THE PASTURE.

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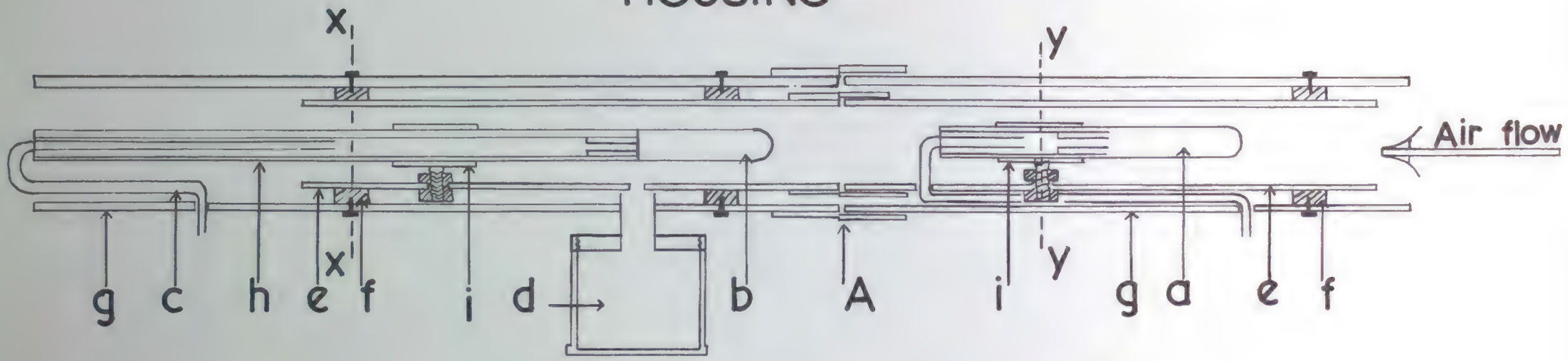
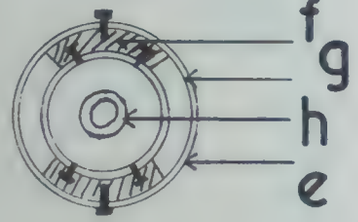
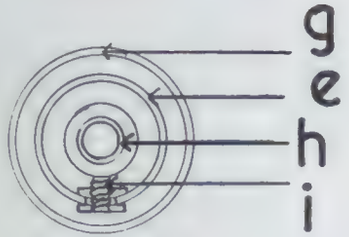
FIG. 2 SECTIONAL VIEWS OF THE PSYCHROMETER HOUSING



Vertical Section



Section through x–x



Section through y–y

Legend:-

(a) Dry bulb
(b) Wet bulb
(c) P.V.C. insulating thermo-couple wires
(d) Distilled water holder
(e) Inner copper tube
(f) Tufnol spacers
(g) Outer copper tube
(h) Paxolin tube
(i) Thermometer holders

Note: The housing can be parted at A. The 'dry' section is a tight push fit into the 'wet' section.

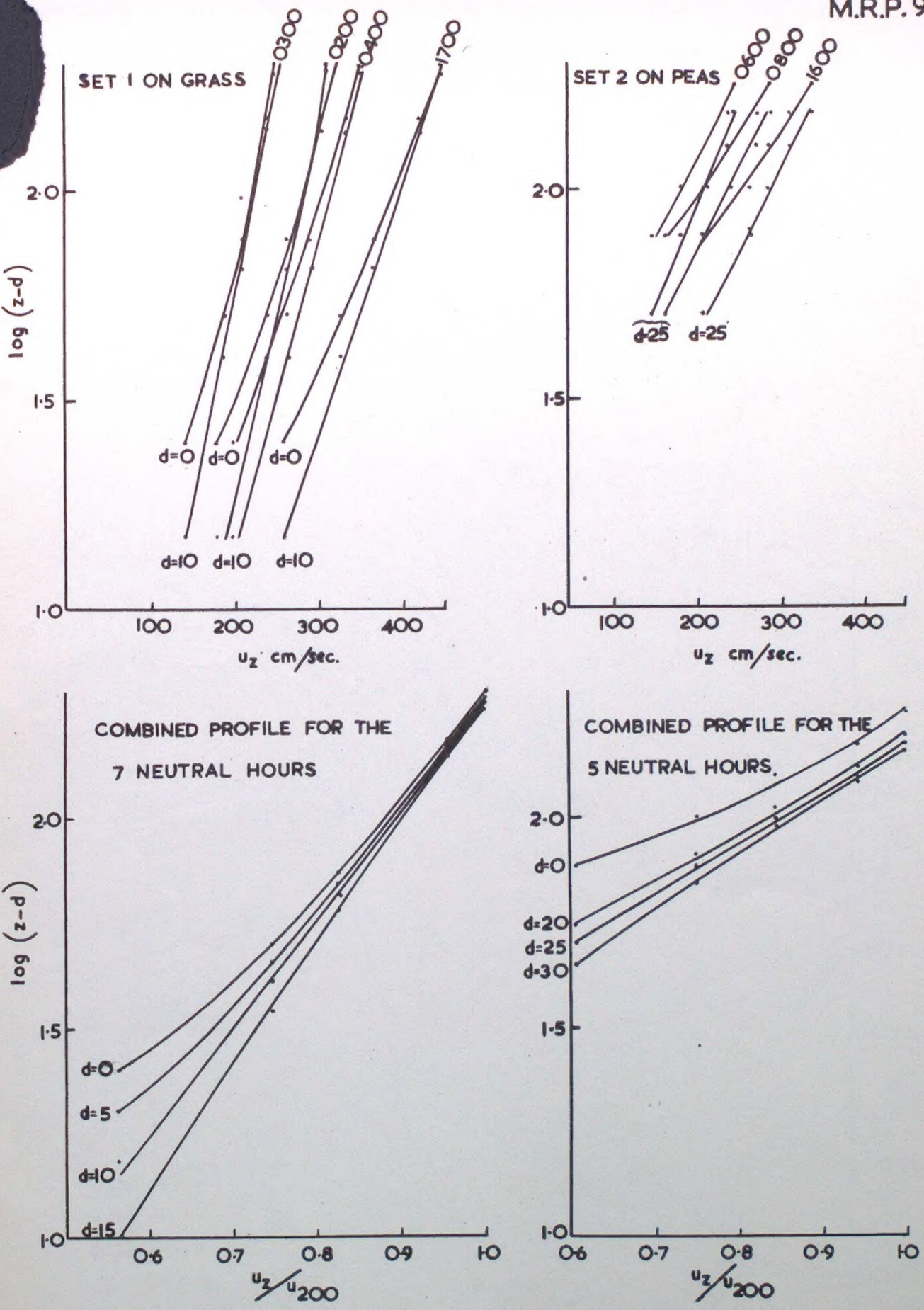


FIG. 3. DETERMINATION OF ZERO PLANE DISPLACEMENT
OBSERVATION NO. 12. 22-23 JUNE 1955.

FIG. 4 COMPARISON OF HUMIDITY MAST PERFORMANCE IN OBSERVATION NO. 14. THREE SETS OVER GRASS. PSYCHROMETER HEIGHTS 25 AND 50 cm.

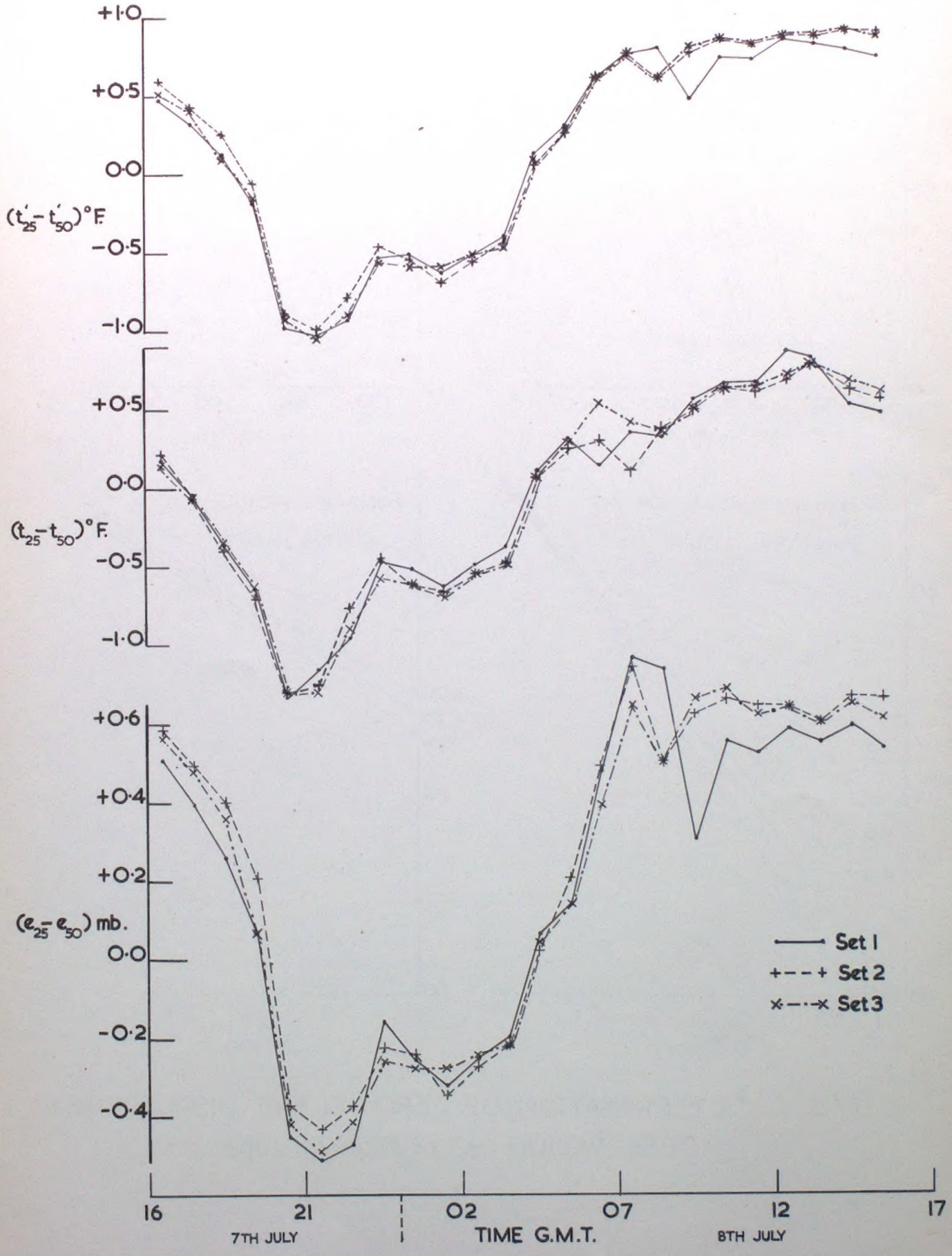


FIG. 5a CURVES OF DRY AND WET BULB TEMPERATURE (t and t') AND DRY AND WET BULB TEMPERATURE DIFFERENCE ($t_1 - t_2$) and ($t'_1 - t'_2$) OVER GRASS, PEAS AND BARE SOIL IN OBSERVATION NO. 10

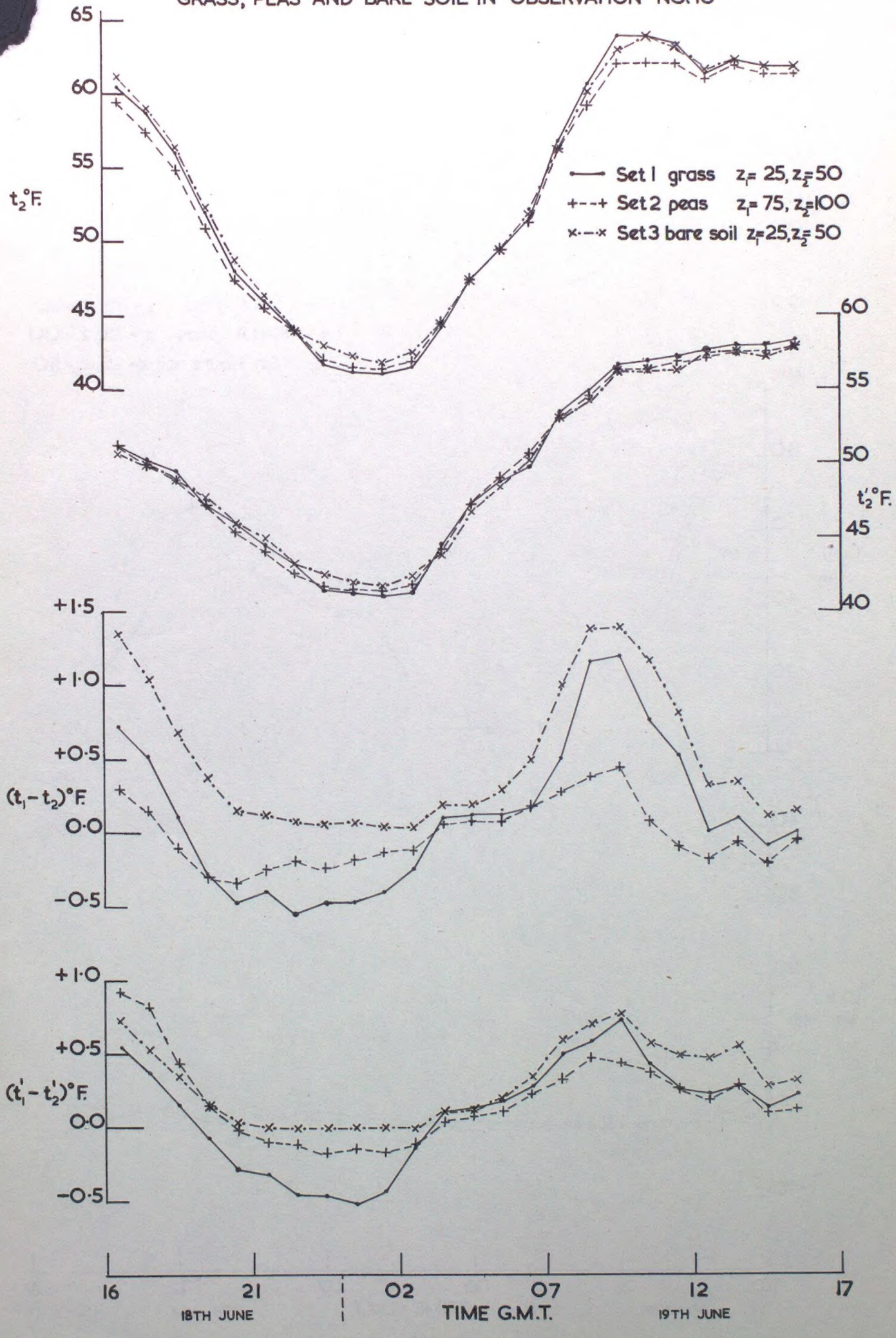
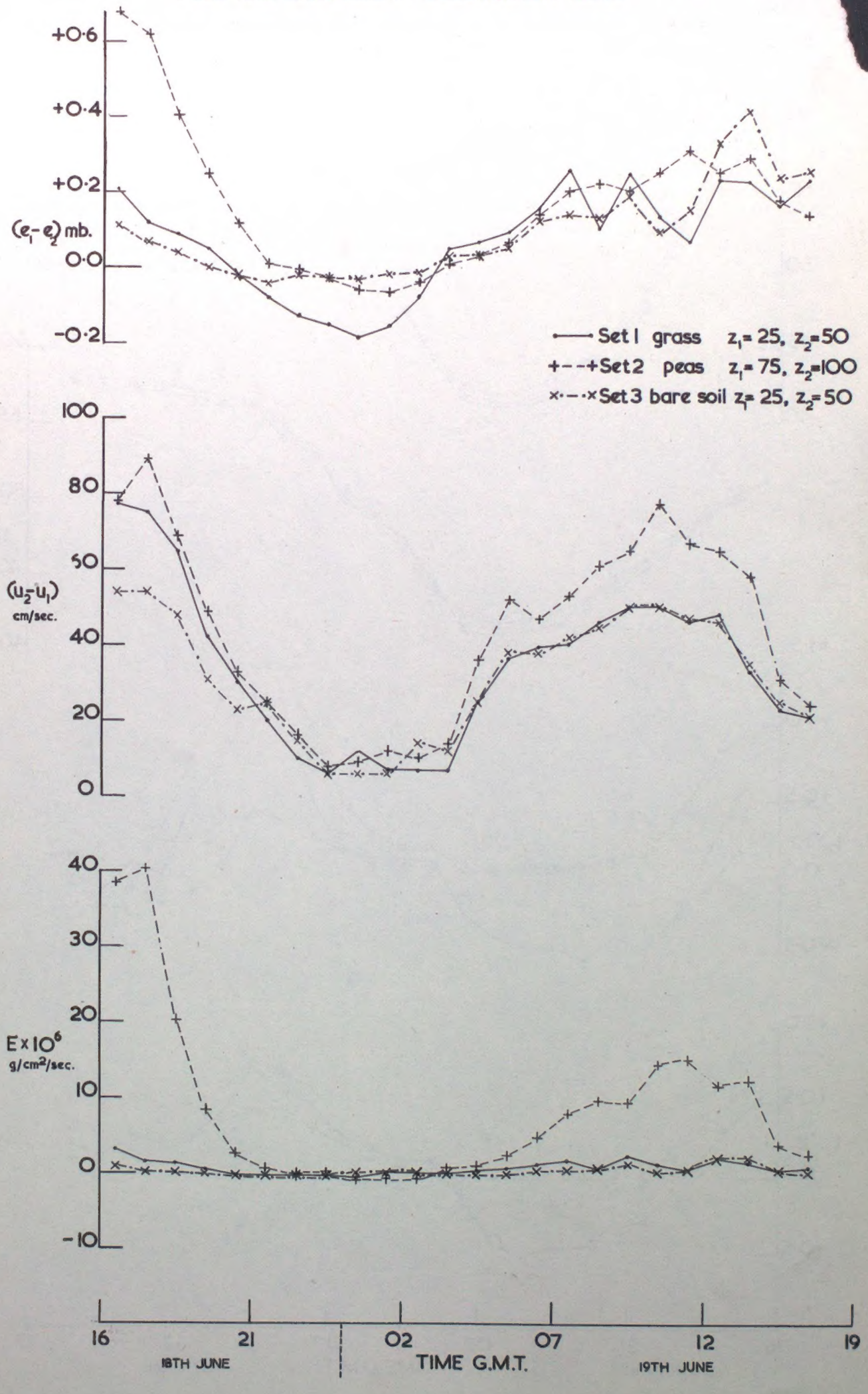



FIG. 5b CURVES OF VAPOUR PRESSURE DIFFERENCE (e_1-e_2), WIND SPEED DIFFERENCE (u_1-u_2) AND RATE OF EVAPORATION E OVER GRASS, PEAS AND BARE SOIL IN OBSERVATION NO.10